

# High Resolution Superconducting Detectors

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NIST, Boulder, CO

## **Detectors**

Microcalorimeters

Transition-Edge Sensors (TES)

SIS Tunnel Junctions (STJ)

(Stephan Friedrich, LLNL)

## **Current Performance**

Energy Resolution

Count Rate

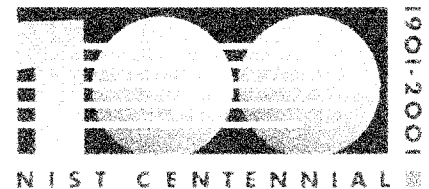
Spectral Quality

## **The Future**

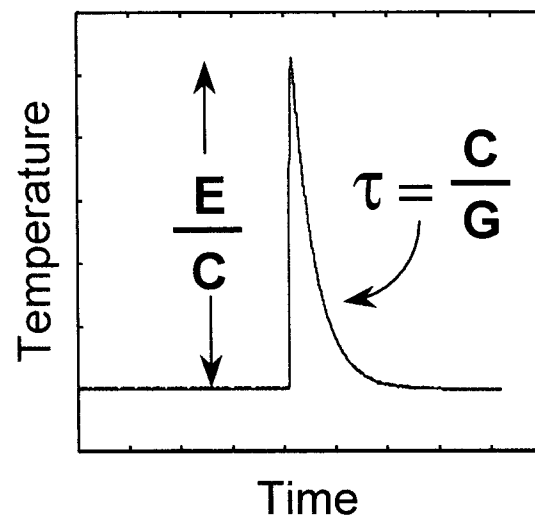
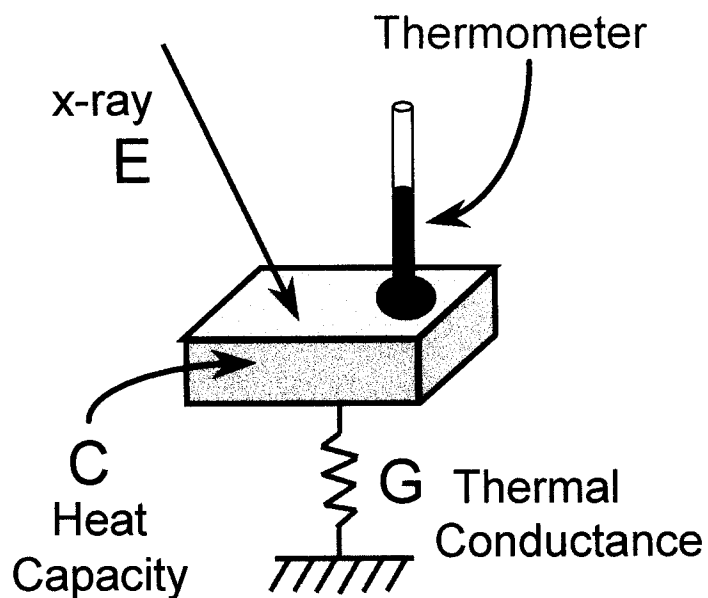
Large Format Arrays

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# Microcalorimeters



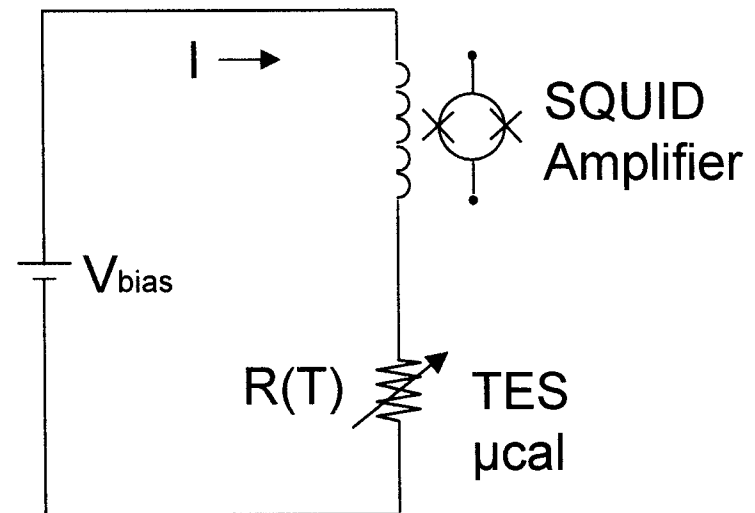
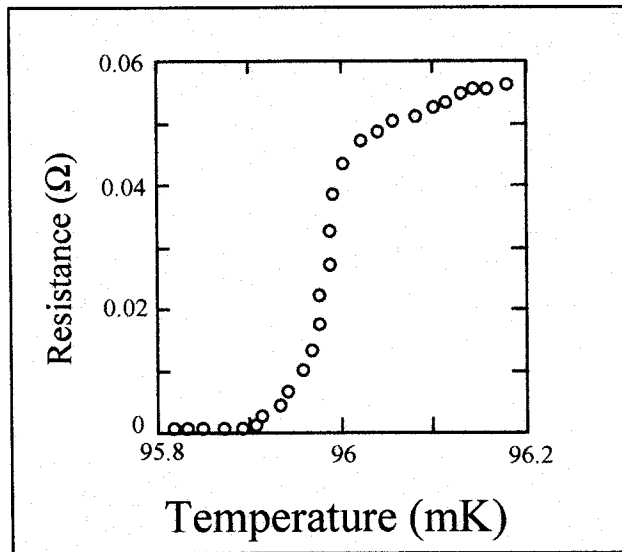
- Resolves single photons
- Good energy resolution (a few eV)  
when operated at low temperature ( $\sim 0.1$  K)

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# Transition-Edge Sensors

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## Superconducting Transition-Edge Sensor (TES)

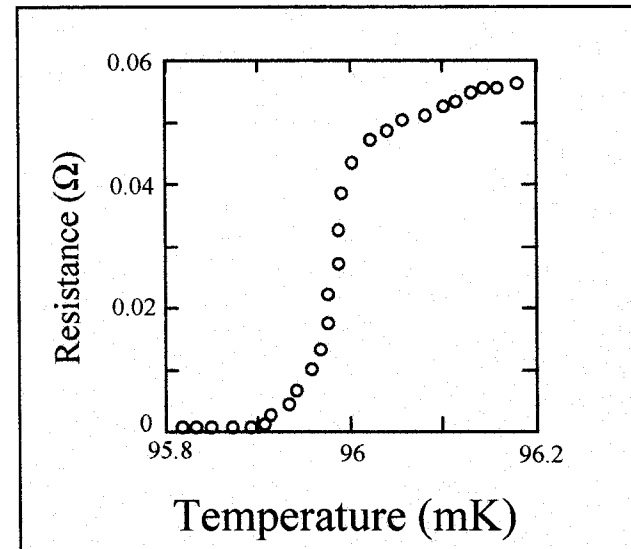
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# Molybdenum-Copper Bilayer

- A bilayer of a thin superconducting film and a thin normal metal acts as a single superconductor with a tunable  $T_c$  - the “proximity effect”
- Molybdenum-copper
  - Robust and temperature stable
  - Molybdenum  $T_c \sim .92$  K
  - Copper normal

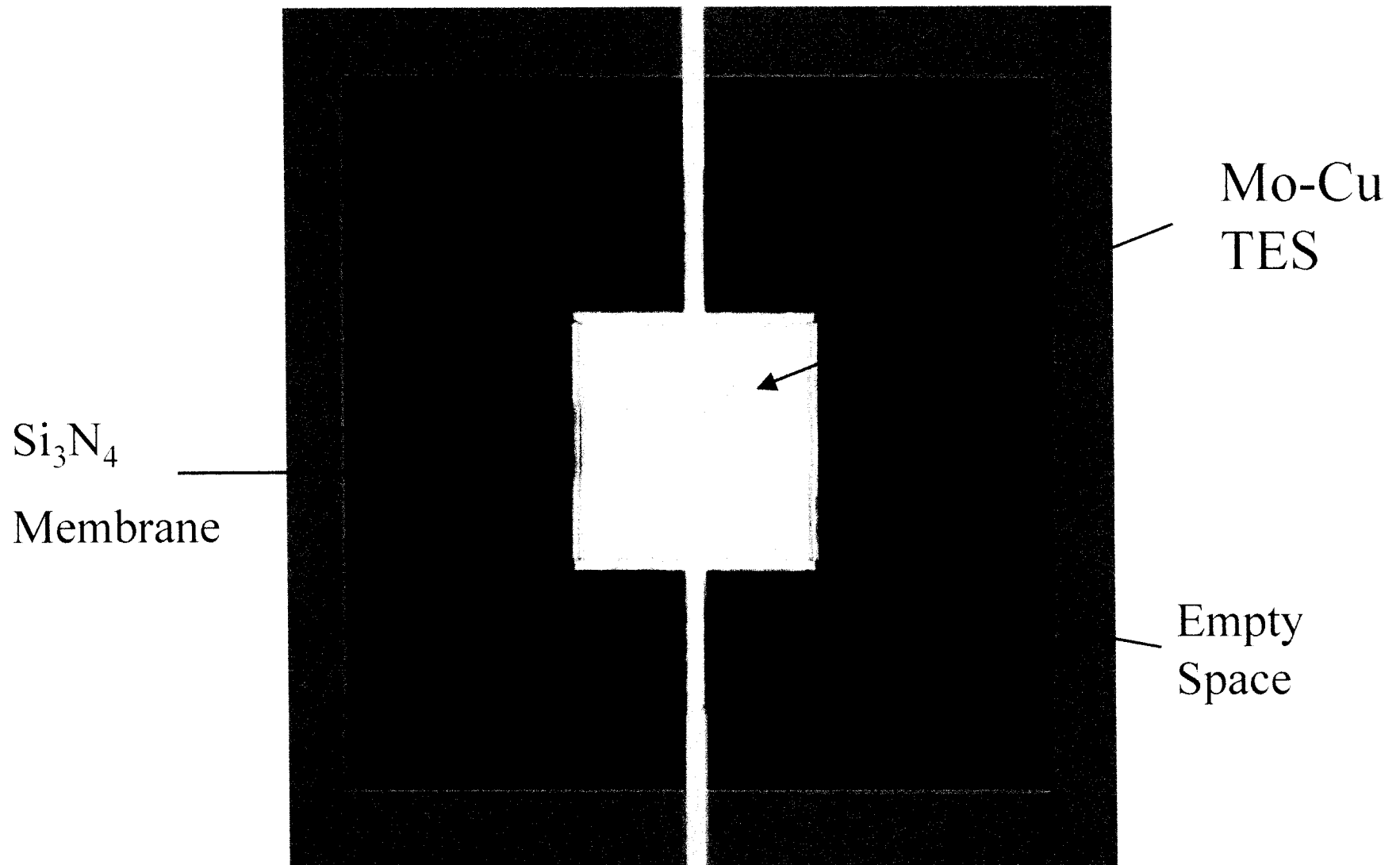
- Sharp
- Reproducible  $< \sim 5$  mK
- Tunable
- Robust



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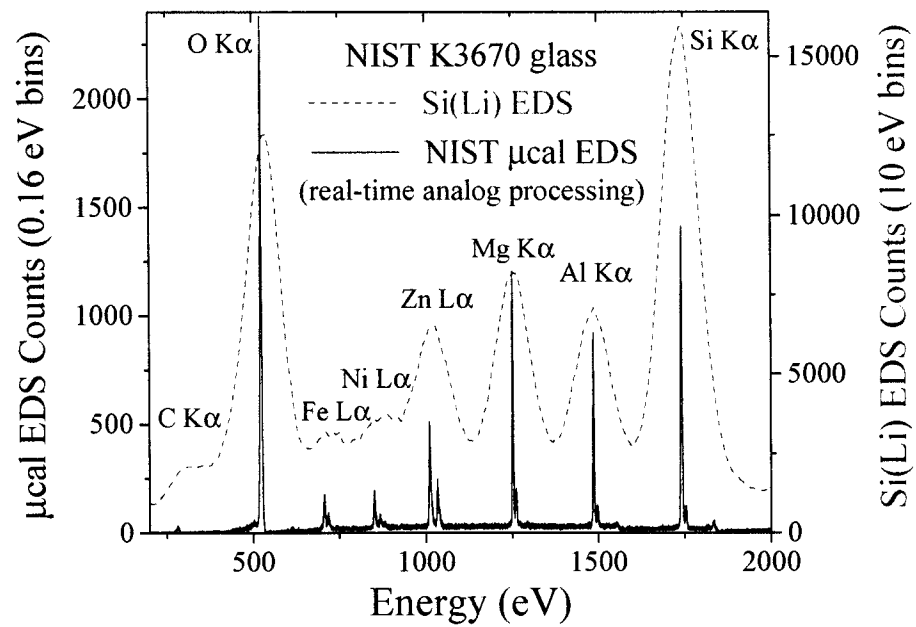
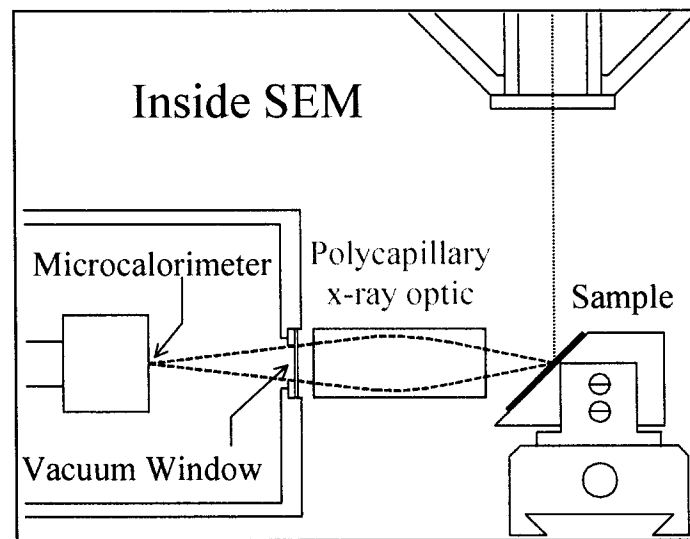
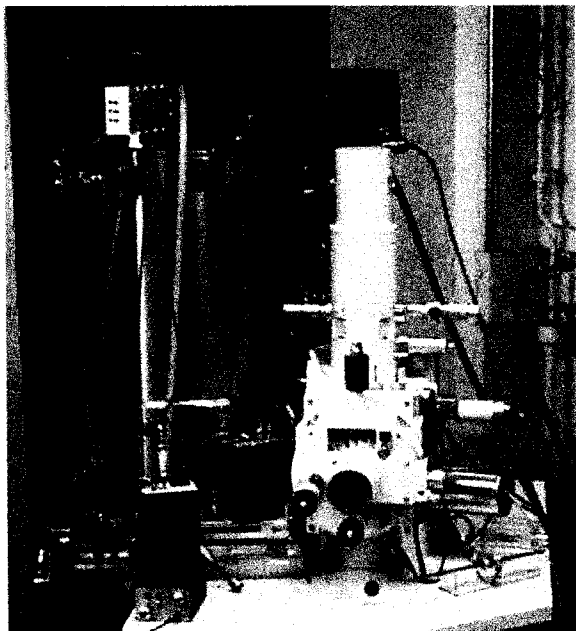
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# Transition-Edge Sensor X-Ray Microcalorimeter



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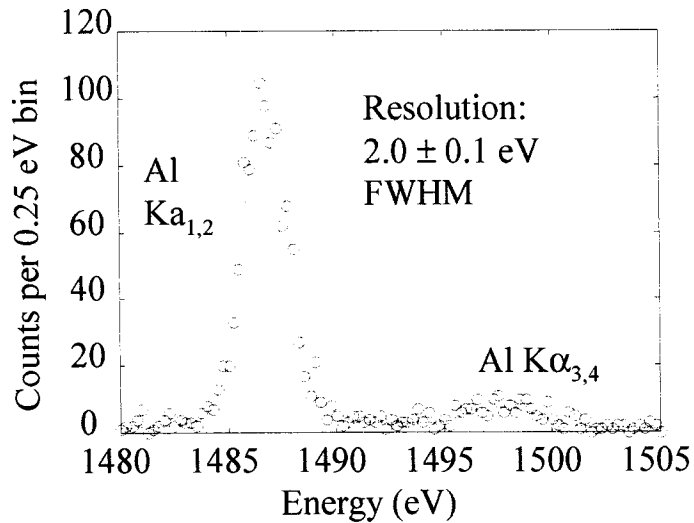


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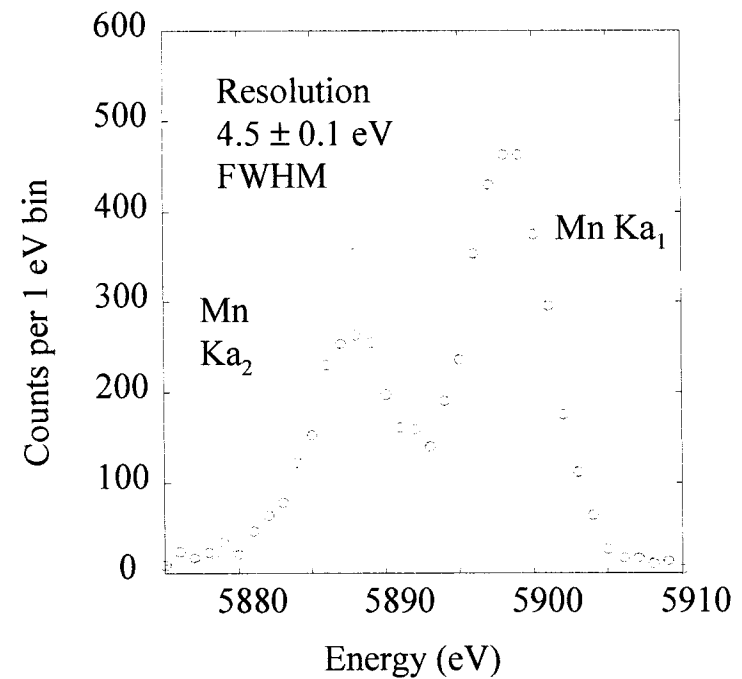
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# TES X-Ray Microcalorimeter

**2.0 eV resolution at 1.5 keV**



**4.5 eV resolution at 6 keV**



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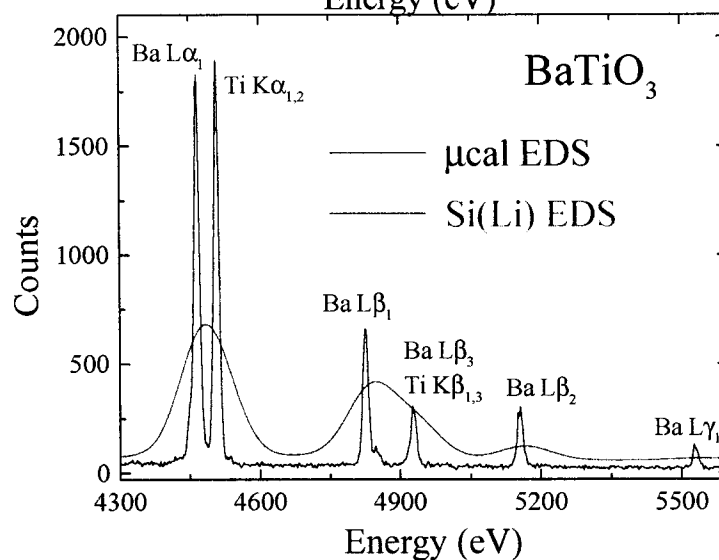
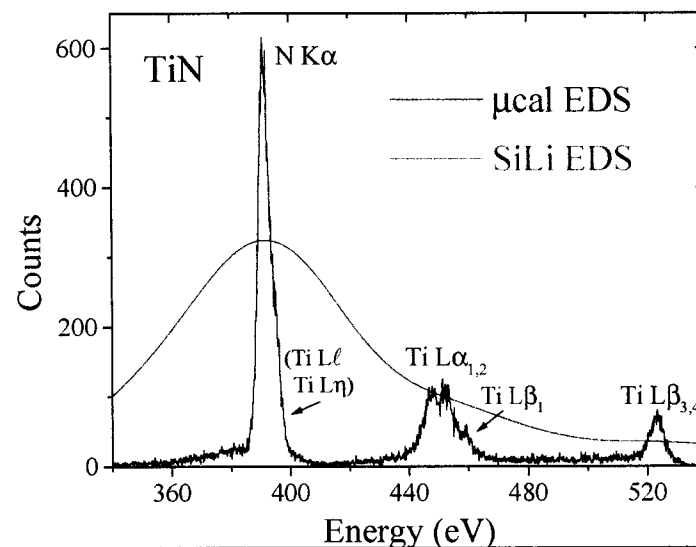
# Resolving Peak Overlaps

NIST's TES x-ray microcalorimeters are being used to solve critical microanalysis problems for the semiconductor industry, such as *contaminant particle identification*.

NIST's single-pixel TES microcalorimeter technology is now being commercialized in the U.S. by **NORAN** and **EDAX**.

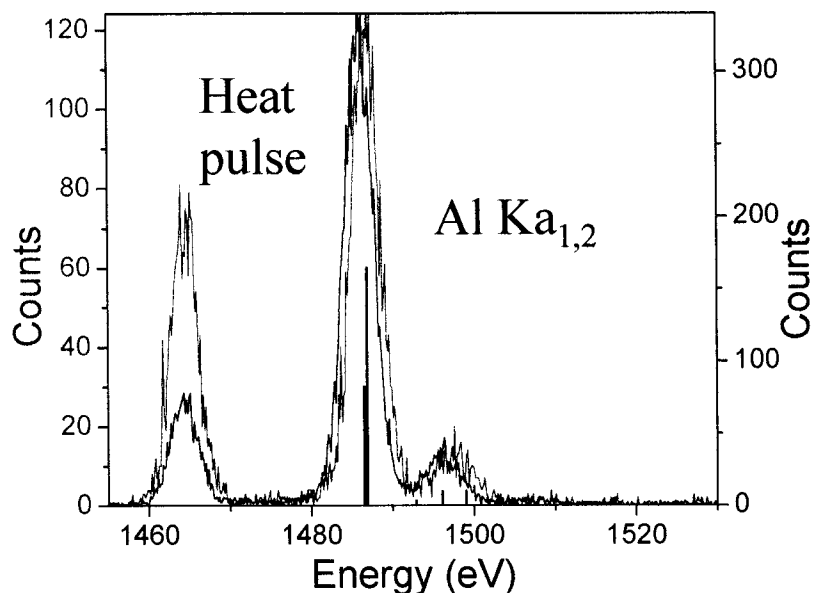
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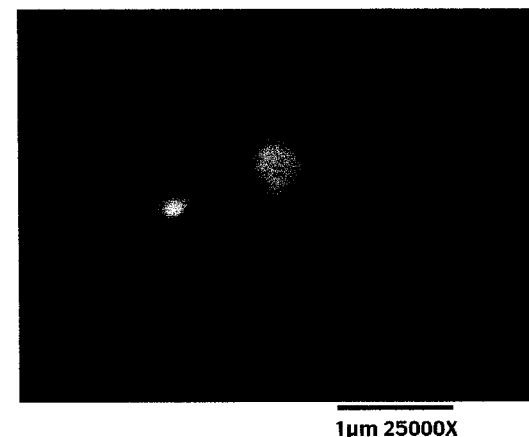




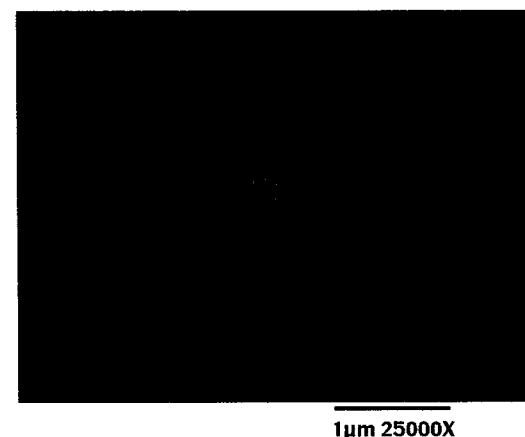
# Chemical Shift in Al - Al<sub>2</sub>O<sub>3</sub>



- Chemical bonding state causes small (< 1 eV) shifts in x-ray line position
- Industrially important problem: Al particles on oxide substrates.



Al oxide particle



Al particle

# Chemical Shift Map

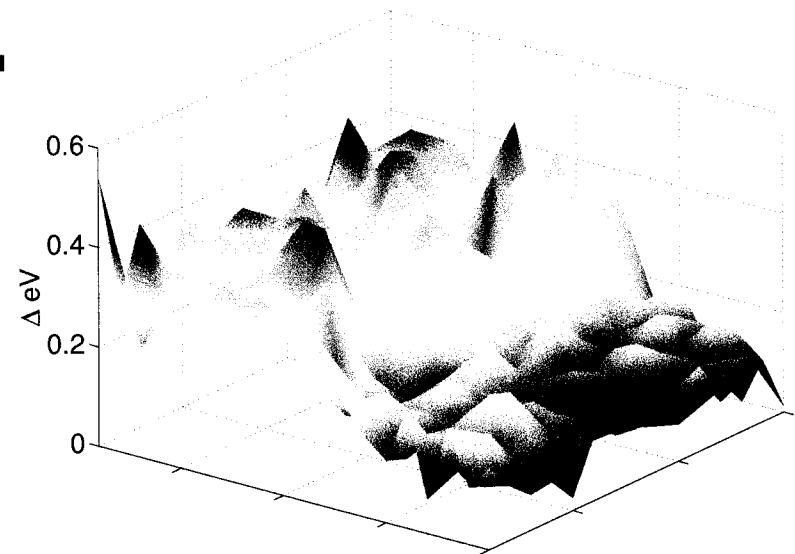
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10 $\mu$ m 2000X

Al oxide

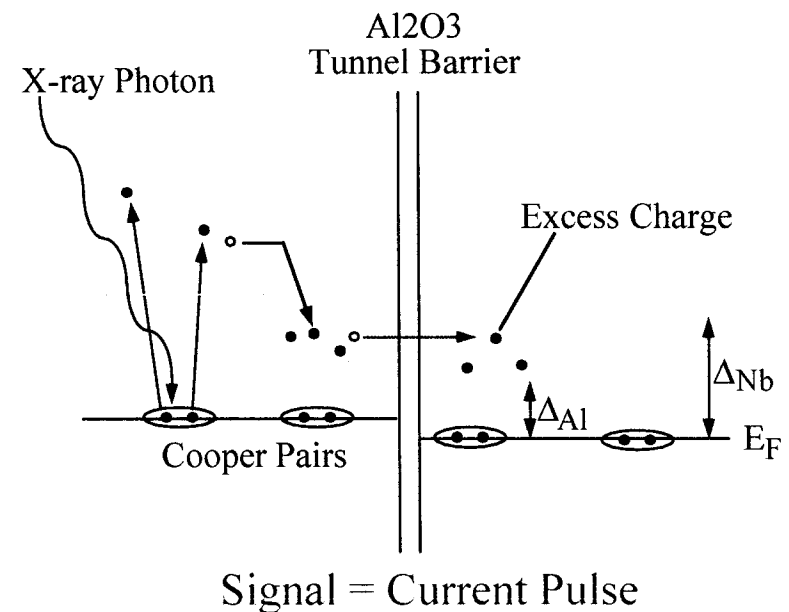
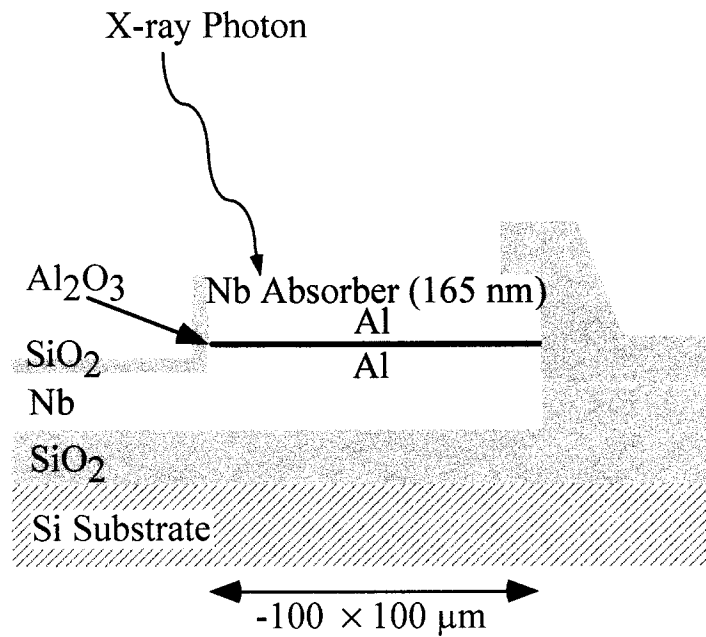
Al



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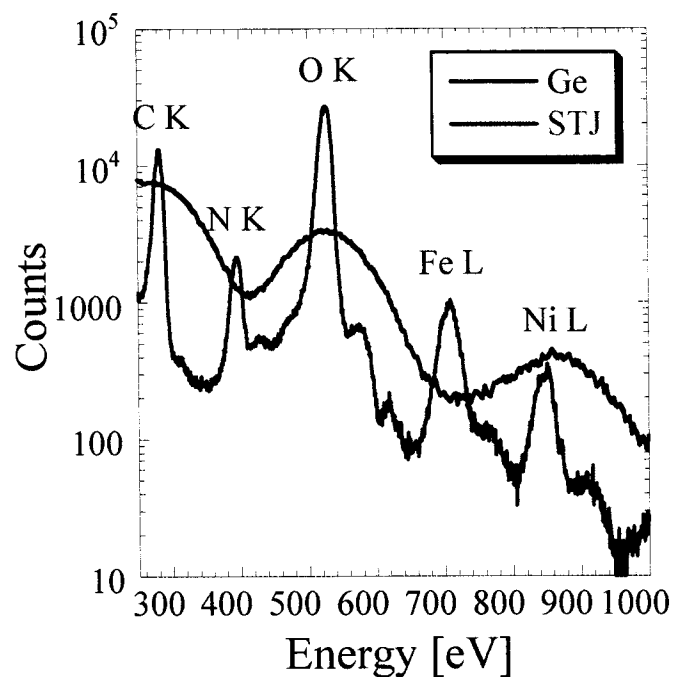
# Superconducting Tunnel Junctions



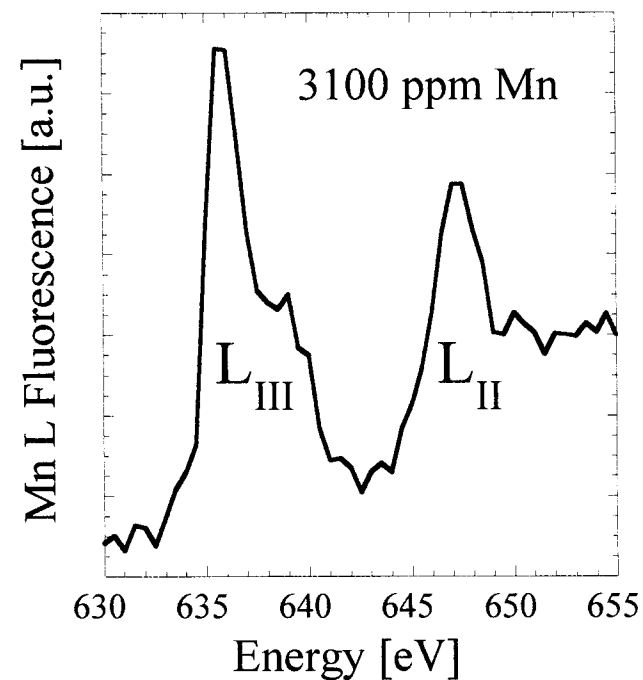
Small energy gap (meV)  $\Rightarrow$  high resolution ( $<10$  eV)

Fast charge decay (few  $\mu\text{s}$ )  $\Rightarrow$  high count rate ( $10^4$  cps)

# Synchrotron X-Ray Fluorescence Data

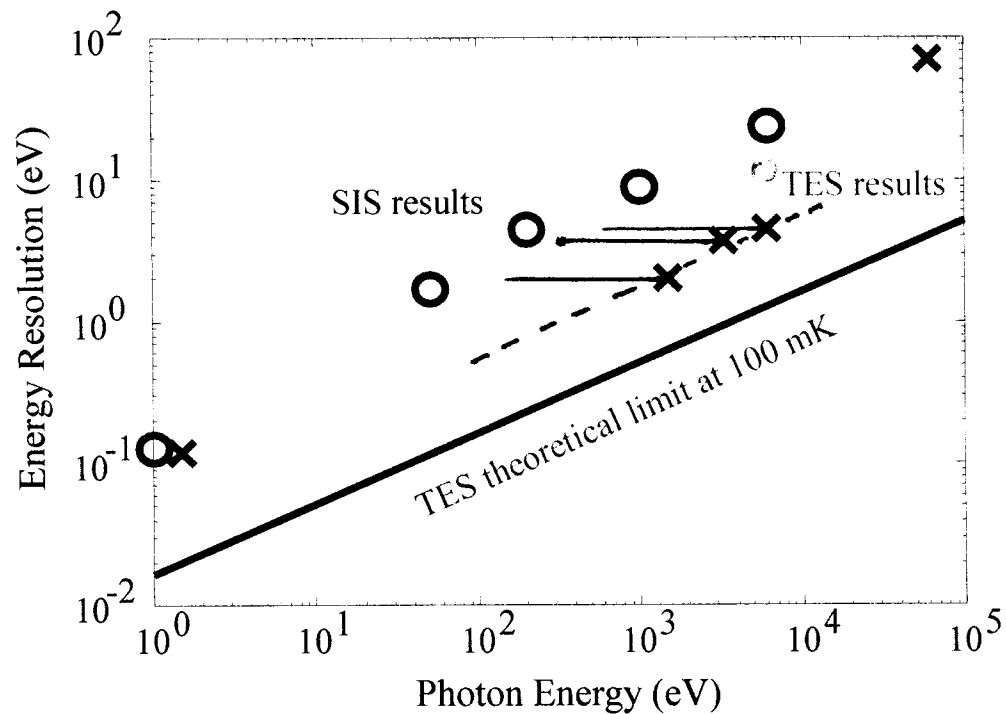


Hydrogenase: 480 ppm Ni



L-edge absorption spectra

# Achieved Energy Resolution



- For visible photons, TES and SIS have similar energy resolution and count rate.
- For soft x-ray, TES has  $\sim 5\times$  better energy resolution; SIS has  $\sim 10\times$  higher count rate

## TES

<u>E</u>	<u><math>\Delta E</math></u>	
• 2.0 eV	0.12 eV	(Stanford)
• 1.5 keV	2.0 eV	(NASA/GSFC)
• 3.3 keV	3.7 eV	(NASA/GSFC)
• 6 keV	4.5 eV	(NIST)
• 60 keV	70 eV	(LLNL)

(TES connected to thick Sn absorber)

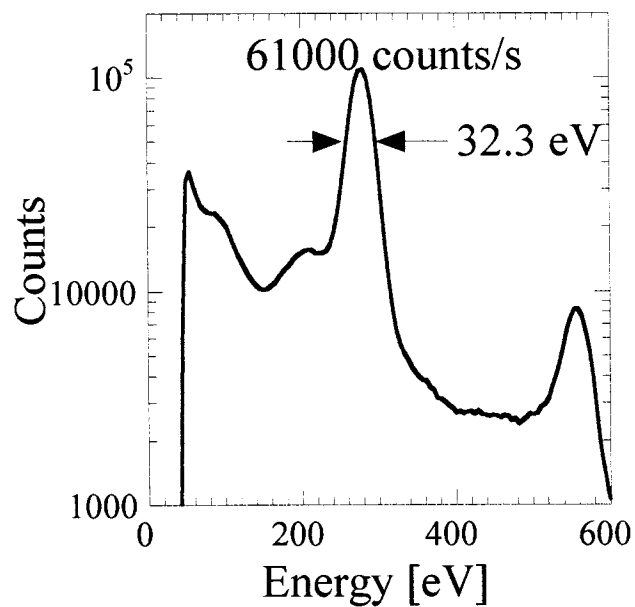
## SIS

<u>E</u>	<u><math>\Delta E</math></u>	
• 1.0 eV	0.13 eV	(ESA)
• 50 eV	1.7 eV	(LLNL)
• 200 eV	4.5 eV	(LLNL)
• 1 keV	8.9 eV	(LLNL)
• 6 keV	24 eV	(LLNL)

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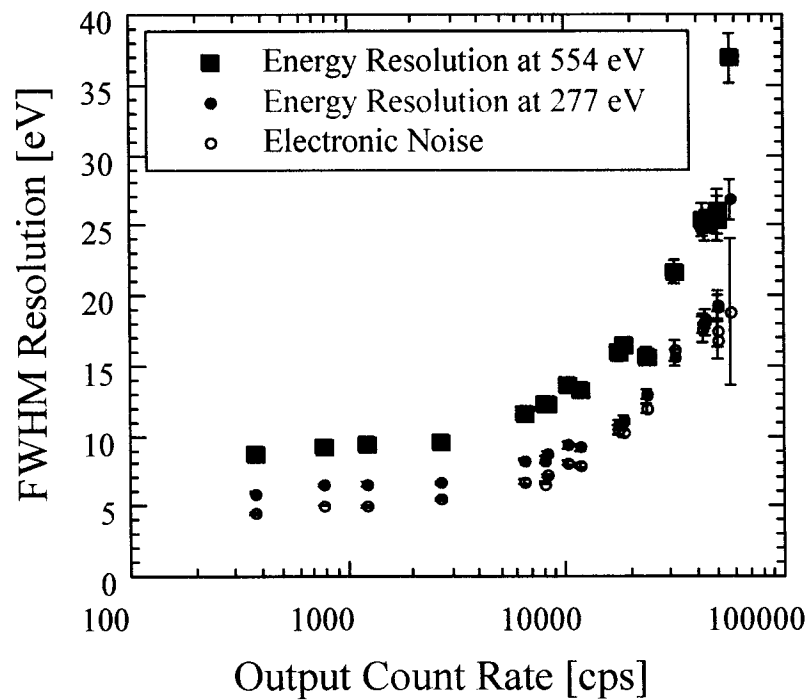
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# STJ High Count Rate Performance



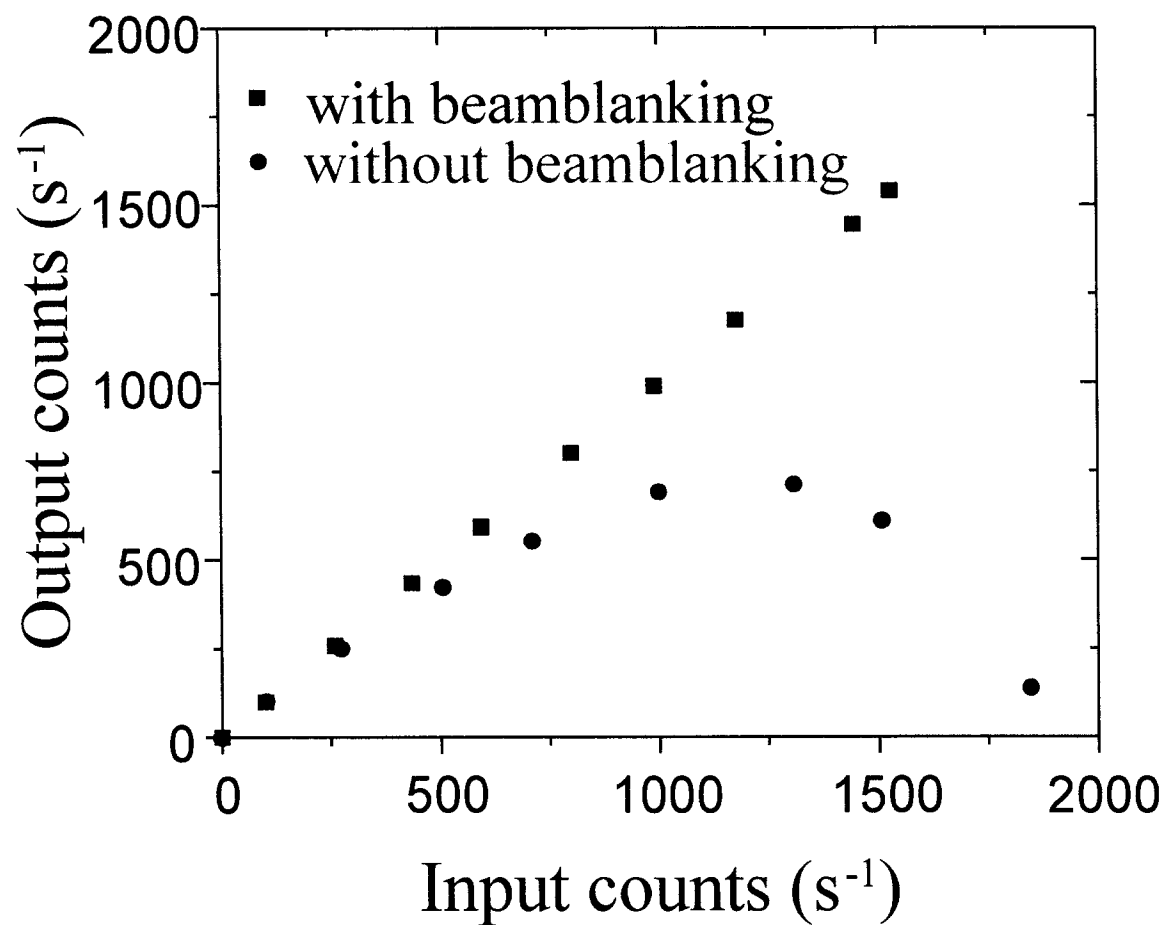
0.25  $\mu$ s shaping time

No pile-up rejection



# TES X-Ray Count Rate

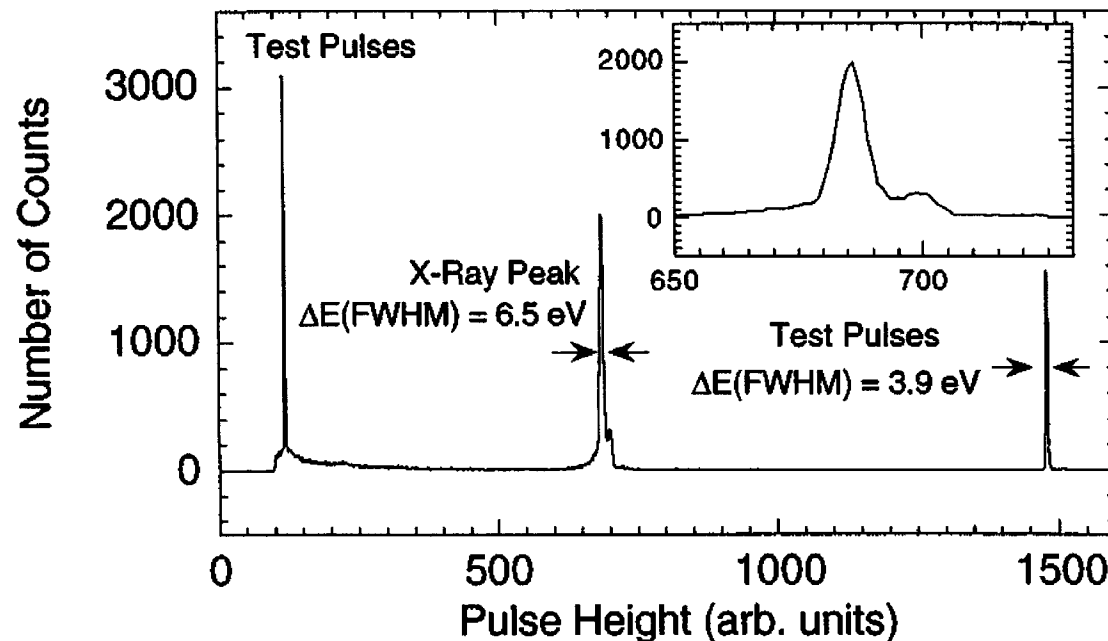
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# SIS Spectral <sup>quality</sup> purity



SIS response to 700 eV x-rays generated using an x-ray monochromator at SSRL

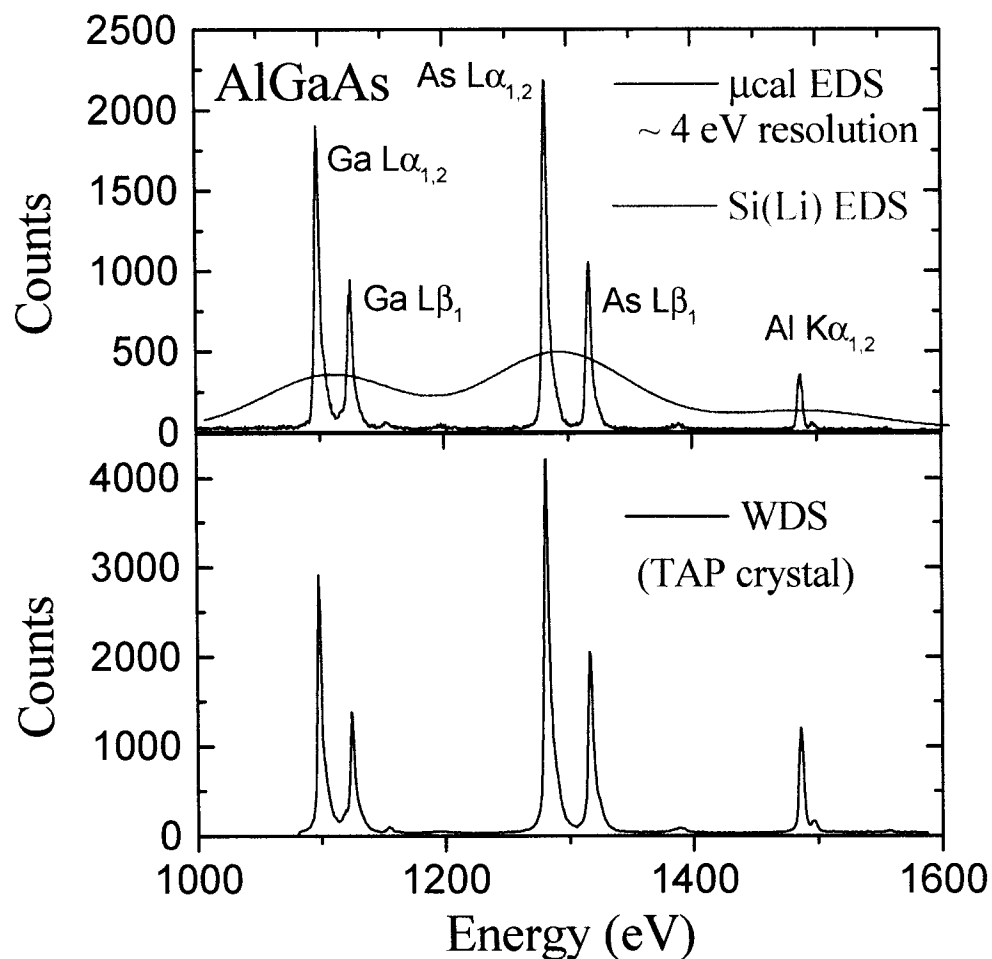
J.B. le Grand et. al., *Appl. Phys. Lett.* 73, 1295 (1998).

- Up to 600 eV, absorption is in top electrode, and the peak is an accurate Gaussian.
- For 650 – 1000 eV, the central line is Gaussian, an extra bump due to base-electrode events occurs above the peak, and a tail due to spatial inhomogeneities extends below the peak. The rest of the spectrum is clean, and free of artifacts.
- Above 1 keV, significant artifacts occur due to base electrode and substrate events.
- **The base-electrode hits can sometimes be removed by a risetime veto**—not a good idea for energy resolution.



# TES Spectral <sup>quality</sup>~~purity~~

- Spectral purity of TES studied by comparing to spectrum of same sample taken by WDS (Bragg Crystal Diffraction.)
- Efficiency varies across spectrum due to bismuth absorber efficiency and Al-coated parylene windows.
- Escape peaks present, as expected
- Otherwise, detector response is accurately modeled as Gaussian (WDS is Lorentzian).



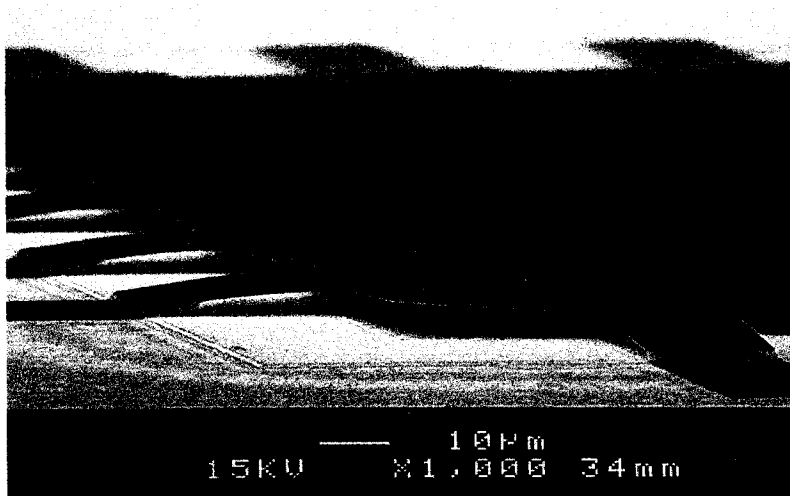
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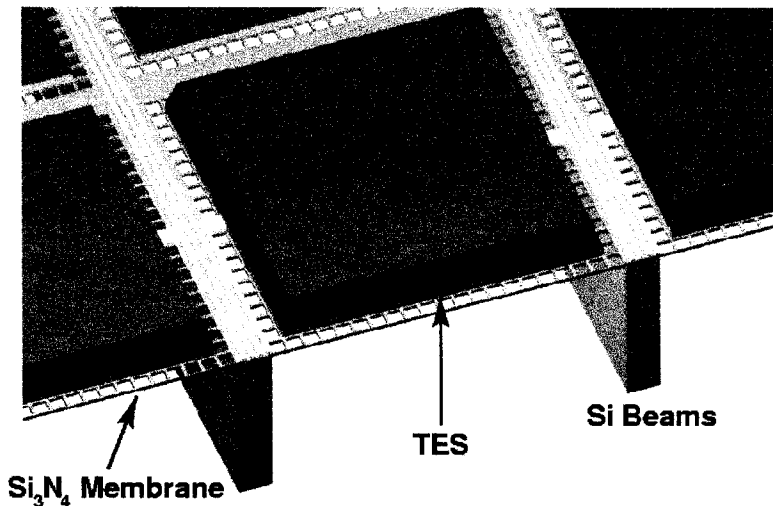
# The Future: Large Format Arrays

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- Increase count rate
- Provide imaging information
- Increase area



Elevated, surface micromachined platform for microcalorimeter



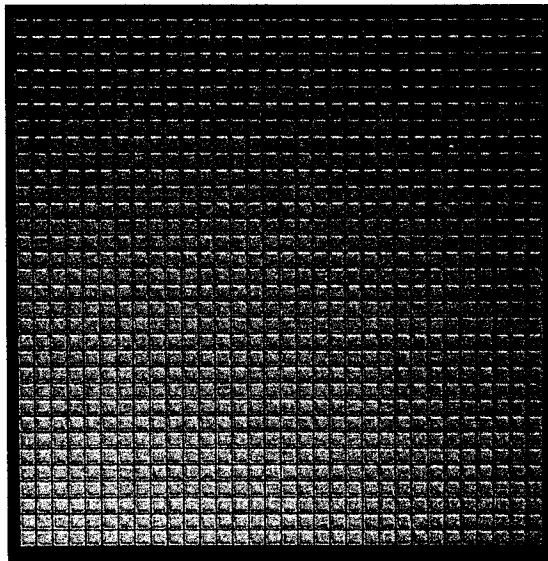
Bulk micromachined microcalorimeter structure (artist's conception)

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# Overhanging absorbers

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32×32 array of overhanging  
bismuth absorber structures  
fabricated at NASA/GSFC

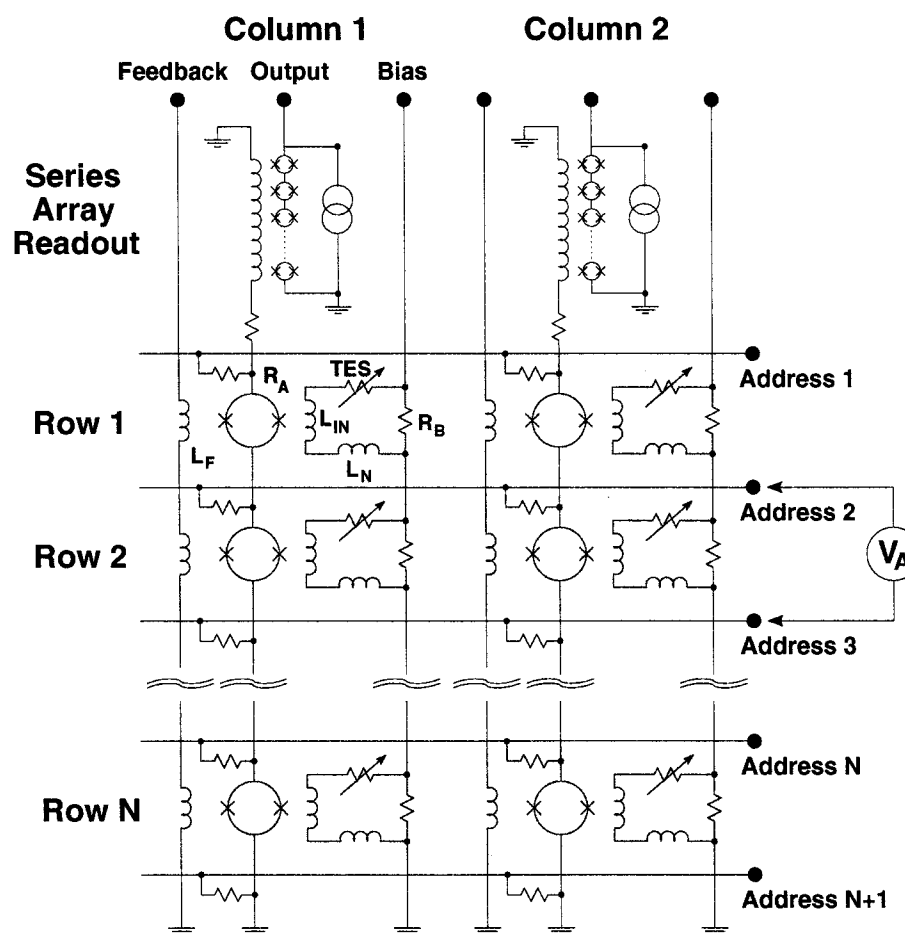
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# SQUID Multiplexer for TES Arrays

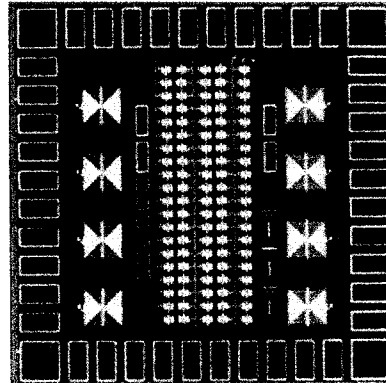
- Multiplexing is necessary for large-format arrays
- Ultra-low power SQUID amplifiers can be operated in the focal plane
- SQUID MUX turns a column of SQUIDs on one at a time
- With proper engineering, no significant loss in single-pixel performance
- Scalable to  $> 10,000$  pixel arrays with  $\sim 100$  readout channels



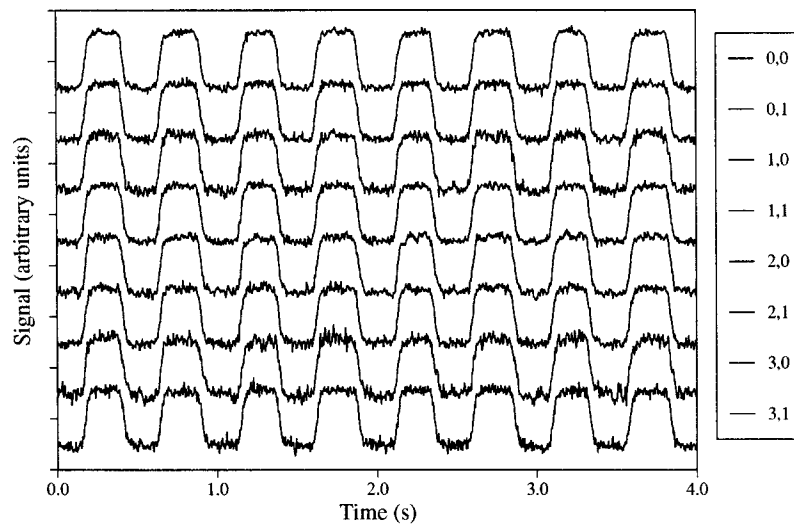
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# Photometric response of multiplexed 8-pixel TES array



8-channel SQUID  
multiplexer



- 8-pixel, multiplexed TES bolometer array
- Output demultiplexed into 8 software channels
- Array exposed to chopped IR signal

# Some Array Projects

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## Existing (or nearly so)

- S-Cam:  $6 \times 6$  array of visible SIS (tested on *William Herschel Telescope*) [ESA]
- 4-pixel TES visible array (tested at *MacDonald Observatory*) [Stanford, NIST]
- 9-pixel SIS soft x-ray array being assembled [LLNL]
- FIBRE: 16-pixel, MUXed TES IR bolometer array (at CSO in 2/2001) [NASA/GSFC, NIST]

## Longer term, funded array projects

- SAFIRE: 12x24 MUXed TES IR bolometer array (first-light SOFIA instrument: 2002-2003) [NASA/GSFC, NIST]
- SCUBA-2: >10,000 pixel TES IR bolometer array On the JCMT in 2006. [UK ATC, NIST]
- Constellation-X:  $32 \times 32$  multiplexed TES soft x-ray array (on-orbit in 2008). [too many to list]



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# Summary of *Soft X-Ray* Performance

## TES

- Soft x-ray single-pixel count rate  $< \sim 1$  kcps
- Excellent resolution
- Area:  $\sim 400 \mu\text{m} \times 400 \mu\text{m}$  per pixel
- Good spectral quality

- Arrays - Better imaging, <sup>Energy</sup> resolution, area  
Compatible with MUX

*Goal:* Multiplexed, 1000-pixel array  
with 100-1,000 kcps

## SIS

- Soft x-ray single-pixel count rate  $> \sim 10$  kcps ( $\sim 10\times$  higher than TES)
- Good resolution ( $\sim 5\times$  less than TES)
- $50 \mu\text{m} \times 50 \mu\text{m}$  to  $200 \mu\text{m} \times 200 \mu\text{m}$   
(most results  $100 \mu\text{m} \times 100 \mu\text{m}$ ).

- Spectral quality

Good below 600 eV <sup>or high efficiency absorber</sup>  
Good above with substrate/electrode veto?

- Arrays - Better count rate  
Need MUX

Now building 9-pixel array with  
 $\sim 100$  kcps

*Goal:* 100-pixel array,  $\sim 1,000$  kcps

The direction of both technologies will be  
influenced by the needs of the synchrotron  
community

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